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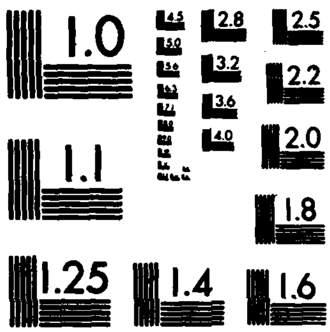

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THREE-DIMENSIONAL TURBULENT BOUNDARY LAYER ON BODY OF REVOLUTION AT INCIDENCE

by

V.C. Patel and B.R. Ramaprian

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FINAL REPORT
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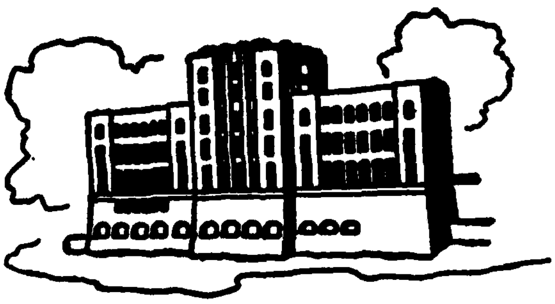

Iowa Institute of Hydraulic Research
The University of Iowa
Iowa City, Iowa

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An experimental and theoretical study of three-dimensional boundary layers on bodies of revolution at incidence was conducted during the period May 1980-July 1983. This final report summarizes the technical accomplishments. Reference is made to the previous reports and papers resulting from the study and some recent experimental results on the boundary layer in the plane of symmetry and the vortex formation region are presented.

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I. INTRODUCTION

This report presents an overview of several different aspects of boundary layers on bodies of revolution investigated under the joint support of the Air Force Office of Scientific Research and the Army Research Office (Grant AFOSR-80-0148) during the period May 1980 through July 1983. Most of the results have been or will be discussed in detail in the publications listed in Appendix I.

II. EXPERIMENTAL STUDIES

One of the primary objectives of ~~the~~ this study was to develop instrumentation for the measurement of the mean flow and the Reynolds stresses in three-dimensional turbulent boundary layers, and to use these to supplement the mean-flow measurements made earlier by Ramaprian, Patel and Choi [1] on the combination body at an incidence of 15 degrees.

II.1 Wall Shear-Stress Measurement Techniques:

A survey of the state-of-the-art indicated that very little was known about the accuracy or consistency of different techniques that have been tried for measuring the wall shear-stress vector in three-dimensional flows. For this reason, a thorough comparative study of these techniques as well as two new ones developed at the IIHR was undertaken. This involved the fabrication of the various probes, their calibration in several different ways, and finally the evaluation of their relative performance in a three-dimensional turbulent boundary layer. The following techniques were investigated:

(i) 3-hole yaw probes (of two different diameters) used as a Preston tube
(ii) a pair of Stanton tubes in V-configuration (sublayer fence)
(iii) McCroskey gage [2] (sublayer)
(iv) Dual hot-wires in V-configuration (sublayer wire)
(v) oil smear (for direction of wall shear stress)

The gages (i)-(iv) were calibrated for magnitude as well as direction of wall shear stress in a two-dimensional flat-plate boundary layer in zero

pressure gradient. The gages were then used to measure the wall shear stress in the three-dimensional turbulent boundary layer in the trailing edge region of a NACA 0012 airfoil with a 30-degree angle of sweep. Measurements were obtained at several angles of incidence.

An oil smear technique was developed specifically for low-speed flow studies. This technique was used to obtain, in each of the above cases, the direction of wall shear stress at the same location on the airfoil where the gages were used. The results of the entire study are summarized by Figures 1 and 2. These figures show the relative performance of the different devices in measuring the magnitude C_f and direction γ) of the wall shear stress. The data scatter (due to random and systematic calibration drifts, positioning errors etc.,) associated with each technique are shown by the error bars. From this study it was concluded that the sublayer fence provided the best means of measuring wall shear stress. The study also showed that use of the commercially available McCroskey-type gages (sublayer films) could give erroneous results.

The results of this study are reported in detail in [3].

II.2 Measurement of Reynolds Stresses.

Considerable effort has been devoted to the development of the methodology and the associated computer software for the simultaneous measurement of all six components of the Reynolds-stress tensor at a point in a 3-D turbulent flow using a triple sensor hot-wire probe. A critical assessment of this method, as used by previous investigators, showed several deficiencies resulting in very poor accuracy. Two alternate ways of processing the three instantaneous signals from the three sensors were developed under this project. These methods were developed with the following basic requirements in view

(a) It should be possible to obtain intensities and stresses with or without accumulating time-series data from the outputs of the three sensors.

(b) The results should be obtainable without the restriction that the probe axis should be aligned with the mean-flow direction.

In one of the above methods (Method A), the instantaneous voltage outputs E_1, E_2, and E_3 from the three sensors are sampled, digitized, and stored. The instantaneous velocities, U, V, and W (referred to a coordinate system fixed to the probe) are later calculated from these time-series data, via the calibration curves, by a solution of a set of three algebraic nonlinear equations. After the entire set of instantaneous velocity components are evaluated, these are time averaged to obtain $\overline{U}$, $\overline{V}$, and $\overline{W}$. The instantaneous turbulent fluctuations u, v, and w are then recovered and used to compute the Reynolds stresses $\overline{u^2}$, $\overline{v^2}$, $\overline{w^2}$, $\overline{uv}$, $\overline{uw}$, $\overline{vw}$. Since there is no linearization involved in this process, the method can be used even for large intensities of turbulent fluctuations and for any orientation of the probe relative to the flow. The method, however, involves iterative solution of simultaneous nonlinear algebraic equations at each instant and is therefore computationally expensive.

The second method (Method B) involves linearization by assuming that the fluctuating velocities u, v, w are small relative to the magnitude of the velocity vector $\vec{Q}$ (note that this is not the same as assuming $u \ll \overline{U}$, $v \ll \overline{V}$, and $w \ll \overline{W}$, which is quite restrictive in 3-D flows of unknown direction). Only one solution of these nonlinear algebraic equations is then required to obtain $\overline{U}$, $\overline{V}$ and $\overline{W}$. After this the instantaneous turbulent velocity components are recovered from the linearized equations and processed to obtain the Reynolds-stress components. This procedure is an order of magnitude faster than Method A and gives acceptable accuracy in all but very highly turbulent flows.

Figure 3 shows typical results for Reynolds shear stress $\overline{uv}$ in a flat plate boundary layer, measured using (i) Methods A and B, (ii) the technique of Gorton and Lakshminarayana [4] (Method C) and an x-wire probe (Sastry [5]).

Further improvements have been incorporated into the methods described above and these are described in detail in Prabhu et al. [6]. A computer program is now available for use with commercially available triple-sensor probes.

II.3 Turbulent Measurements in the Plane of Symmetry:

As a first step towards obtaining Reynolds-stress data in the boundary layer over the body of revolution, detailed hot-wire measurements were made in the plane of symmetry boundary layer using conventional x-wire probes. In addition to providing a check on the triple-wire probe measurements to be made later, the plane-of-symmetry data are of interest in their own right since they can be used to assess the influence of mean flow covergence and divergence on the turbulence.

Most previous turbulence measurements in three-dimensional boundary layers have been confined to geometries in which the flow along any plane of symmetry that is present is divergent. On the other hand, the boundary layer on the leeside of a body at incidence is initially convergent. Also, as a free vortex type of separation develops, the flow within this boundary layer becomes divergent in the inner part while remaining covergent in the outer part. The response of the turbulence to this complex lateral straining is not known. The present data should therefore be valuable in the evaluation of this feature.

Typical turbulence measurements in the leeward plane of symmetry, obtained with cross wires in two configurations, are illustrated in Figures 4 and 5. Of particular interest are the differences in the distributions at ..ations 3(X/L = 0.333) and 6(X/L = 0.648) since the former is in the region where the mean flow converges into the plane of symmetry while at the latter station the flow in the inner part of the boundary layer is divergent. The covergent-divergent flow at station 6 is responsible for the development of a two-layer structure is the turbulence distribution: a region of higher stresses close to the wall associated with the diverence and an outer region of relatively low stresses associated with the local convergence. The two regions are separated by a distinct plateau, particularly in the normal stresses. Since the divergence on the leeside controls the free-vortex or open type of separation on the body, and the boundary layer on the leeside is particularly sensitive to the initial conditions, it is important to predict the flow along the leeward plane of symmetry with accuracy.

The present plane-of-symmetry data and the somewhat limited data obtained at the DFVLR on a 6:1 spheroid are being analyzed and used to test the performance of boundary-layer calculation procedures. A detailed description of this aspect of the study will be included in the forthcoming Ph.D. dissertation of Baek [7].

II.4 Mean-Flow Measurements in the Vortex Formation Region and Wake:

The measurements in the boundary layer on the combination body were made with an internally-mounted probe-traverse mechanism. Since this could not be used for measurements in the ever-thickening viscous-layer in the region of vortex formation on the leeside and in the wake, an external traverse was constructed. This is capable of tranversing pitot and hot-wire probes normal to the body surface over a large part of the body. Upto the present time, it has been used, in conjuction with a five-hole pitot probe, to measure the three components of mean velocity and the static pressure at several sections downstream of station 6 (i.e. $X/L \geq 0.648$).

Since these experiments were completed in late August 1983, the data are still being analyzed and will be reported in detail in the M.S. thesis of Baban [8]. However, typical results at two cross-sections are illustrated in Figures 6 and 7. These figures show the magnitude (Q) of the velocity vector and the pitch and yaw angles of the velocity vector with respect to the local generator. Figure 6 shows the magnitude Q at θ = 180° and θ =165° for Station 7 (x/L = 0.759) and at θ =165° for station 8 (x/L = 0.870). It is interesting to note that at all the locations, the velocity distributions exhibit s-shaped profiles. Note also that the measurements have been extended well beyond the boundary layer in order to map the flow characteristics in the outer inviscid layer. Figures 7(a) and 7(b) show the yaw and pitch angles at θ =165° for the two stations 7 and 8. It can be seen that at both stations the circumferential flow component near the wall is from the leeward to the windward side (as indicated by negative yaw angle) while in the outer layer, the circumferential flow component is reversed in direction. Notice also that the yaw angle reaches a maximum in the outer layer and decreases as the distance from the wall increases. The pitch angle is also seen to be negative in the inner layer and positive in the outer layer, ultimately approaching the

value corresponding to the freestream direction. The pitch and yaw information together indicate clearly the presence of a vortex (or strong vorticity). This is a fact very much in qualitative agreement with the calculations for a spheroid shown in Figure 9 to be discussed later. Interestingly, static pressure measurements (obtained as an additional result from the 5-hole yaw probe traverses but not shown here) indicated a pressure minimum in the middle of the boundary layer, thus suggesting the existence of a vortex. A more detailed picture of the flow field will be presented in the forthcoming thesis of Baban [8].

III. COMPUTATIONAL STUDIES

The aim of this aspect of the investigation was to develop a method for the calculation of three-dimensional boundary layers on bodies at incidence and study its capabilities for the prediction of separation.

Two different numerical procedures for the solution of laminar and turbulent boundary-layer equations were pursued during the course of this project. Comparisons between the solutions by the two methods and experimental data obtained at Iowa on the combination body and at the DFVLR in Germany on a 6:1 spheroid, presented in [9], indicated that both methods performed well in regions were the boundary layer remains thin enough for first-order equations to remain valid. However, since the ADI method is more versatile, insofar as it can handle circumferential flow reversals and can be readily extended to arbitrary body geometries, such as airplane fuselages, further effort was devoted to establish its limits of validity. The latest results obtained with this method are reported fully in [10] and [11].

Comparisons with the DFVLR data at an incidence of 10° and low Reynolds numbers, when the boundary layer is laminar over a large part of the body, indicate excellent agreement in almost all respects. These solutions were examined in detail in order to resolve the extensive controversy in the literature concerning the definition of separation in three-dimensional flows. Although boundary-layer calculations reproduce many of the symptoms associated with separation, such as a rapid thickening of the viscous flow and the generation of strong longitudinal vorticity, a major conclusion to emerge from these studies is that they cannot, by themselves, be used to <u>define</u>

separation. There is now strong numerical evidence to suggest that the equations develop a singularity in the neighborhood of the line of circumferential-flow reversal and therefore it is not possible to obtain a realistic topology of the flow at separation from their solutions, regardless of the numerical method used. However, the present solutions provide a practical guideline for the determination of the separation line on a body at incidence. It is shown that such a line begins at a point of zero wall shear stress and lies a very short distance to the leeside of the line of circumferential flow reversal. Such a definition is useful in the devlopment of inviscid-flow models to represent separated flow and vortices emanating from elongated bodies at incidence.

At the higher Reynolds number, the flow on the DFVLR spheroid became turbulent after natural transition along a curved line. The calculations presented in [10,11] are among the most complex three-dimensional boundary-layer computations to be attempted to date. Typical results are reproduced in Figures 8 through 10. Figure 8 shows that the calculated wall shear-stress distribution agrees very well with the measured distribution in the laminar as well as the turbulent flow regions. Also, the calculations indicate near zero stress, and hence singular separation, at X/L = 0.88 and $\theta \sim 120°$, again in substantial agreement with the data. Figure 9 shows that the calculations experience no difficulty in handling circumferential flow reversal and clearly show the development of a longitudinal vortex in a thickening boundary layer. Detailed velocity profiles shown in Figure 10, however, indicate that the calculations with the potential-flow as well as the measured pressure distributions agree well with the measurements only in the region where the boundary layer remains thin. Although the thick boundary layer and vortical flow are predicted qualitatively, the disagreements in the details are not small and are attributed to strong viscous-inviscid interaction. Two major conclusions are drawn from this study.

1. The ADI method has been validated in one of the most complex three-dimensional boundary layer flow upto the limits of applicability of first-order boundary-layer theory. Thus, it is now ready for use in the calculation of boundary layers on bodies of arbitrary shape, e.g.,

aircraft fuselages. Provided the boundary layer remains thin, the method can be used to predict the line of separation with confidence.

2. There exist extensive regions of thick boundary layer and vortical flow on elongated bodies of practical interest even in the absence of separation. Although boundary layer methods may provide a quantitative description of such flows, it is necessary to develop procedures which utilize higher-order equations and take into account viscous-inviscid interaction for a more satisfactory solution in these regions.

Attempts have also been made to incorporate some of the higher-order terms, e.g., variation of the coordinate metrics in the normal direction and transverse diffusion, in the equations solved by the ADI method. However, the results do not indicate a dramatic improvement in the prediction of the flow in the thick boundary layer. Thus, it appears that it is necessary to allow the pressure to vary across the boundary layer and relax the pressure field around the body through viscous-inviscid interaction. The extension of the ADI method for this purpose is non-trivial since it is unlikely that the classical displacement-thickness or surface-transpiration approaches will be successful in handling the large traverse gradients of boundary-layer thickness. A more promising approach appears to be the solution of the so-called partially-parabolic or parabolized Navier-Stokes equations through successive iterations. Such methods have been found to be quite successful in the prediction of internal flows but, to the authors' knowledge, applications to three-dimensional external flows are quite limited. A partially-parabolic solution procedure is being developed and tested in two-dimensional and axisymmetric external flows.

IV. CONCLUDING REMARKS

A task that could not be accomplished during the project period is the measurement of the Reynolds stresses in the boundary layer off the plane of symmetry due to the considerable effort that had to be devoted to the development and testing of the triple-wire probe. This phase of the

experimental study was postponed in favor of the turbulence measurements in the plane of symmetry and the mean-flow measurements in the region of vortex formation and open separation and in the wake. A study of the commerically available triple-wire probes indicated that they may not yield reliable data in the thin boundary layer on the body due to the relatively large sensing volume and the interference due to the probe supports. Nevertheless, it is believed that such measurements should be attempted in the future with specially fabricated miniature probes and a slender probe-transverse mechanism.

The computational study has clearly demonstrated the capabilities and limitations of the boundary-layer calculation method. Future effort should be devoted to the problem of strong viscous-inviscid interactions associated with vortex formation and open separation. A practical approach is the solution of the partially-parabolic or partially-elliptic equations. Although some methods for their solution are available for internal flows and a few attempts have been made to obtain solutions in two-dimensional external flows, the flow on a body of revolution at incidence provides a better test case to ascertain the full potential of this approach.

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[7] Baek, J.H., "Boundary Layers on Bodies of Revolution at Incidence, with Special Emphasis on the Flow in the Plane of Symmetry", Ph.D. Dissertation, Mechanical Eng., The University of Iowa, Dec. 1983.

[8] Baban, F., "Mean Flow Measurements in the Vortex Formation Region and Wake of a Body of Revolution at Incidence", M.S. Thesis, Mechanical Eng., The University of Iowa, Dec. 1983.

[9] Patel, V.C. and Baek, J.H., "Calculation of Three-Dimensional Boundary Layers on Bodies at Incidence", Presented at the 7th U.S. Air Force and Federal Republic of Germany Data Exchange Agreement Meeting, Aberdeen Proving Grounds, May 26-27, 1982. Also IIHR Report 256.

[10] Patel, V.C. and Baek, J.H., "Calculation of Boundary Layer and Separation on a Spheroid at Incidence", Presented at the 2nd Symposium on Numerical and Physical Aspects of Aerodynamic Flows", Long Beach, California, January 16-20, 1983.

[11] Patel, V.C. and Baek, J.H., "Boundary Layers and Separation on a Spheriod at Incidence", submitted to AIAA Journal, Aug. 1983.

APPENDIX I. PUBLICATIONS UNDER THE SPONSORSHIP OF THIS GRANT

Craig, W.O., "Measurement of Wall-Shear Stress in Three-Dimensional Flows", M.S. Thesis, Mechanical Eng., The University of Iowa, Iowa City, July 1982.

Prabhu, A., Sarda, O.P., Ramaprian, B.R. and Novak, C.J., "A Method for Making Three-Dimensional Turbulence Measurements Using a Triple-Sensor Hotwire Probe", IIHR L.D. Report 94, Aug. 1982.

Patel, V.C. and Baek, J.H., "Calculation of Three-Dimensional Boundary Layers on Bodies at Incidence", Presented at the 7th U.S. Air Force and Federal Republic of Germany Data Exchange Agreement Meeting, Aberdeen Proving Grounds, May 26-27, 1982. Also Iowa Inst. Hydraulic Research, The University of Iowa, IIHR Report 256, Sept. 1982.

Patel, V.C. and Baek, J.H., "Calculation of Boundary Layer and Separation on a Spheroid at Incidence", Proc. 2nd Symposium on Numerical and Physical Aspects of Aerodynmaic Flows", Long Beach, CA., January 16-20, 1983, pp.---.

Patel, V.C. and Baek, J.H., "Boundary Layers and Separation on a Spheroid at Incidence", submitted to AIAA Journal, July 1983.

*Baek, J.H., "Boundary Layers on Bodies of Revolution at Incidence, with Special Emphasis on the Flow in the Plane of Symmetry", Ph.D. Dissertation, Mechanical Eng., The University of Iowa, Dec. 1983.

*Baban, F., "Mean Flow Measurements in the Vortex Formation Region and Wake of a Body of Revolution at Incidence", M.S. Thesis, Mechanical Eng., The University of Iowa, Dec. 1983.

*under preparation

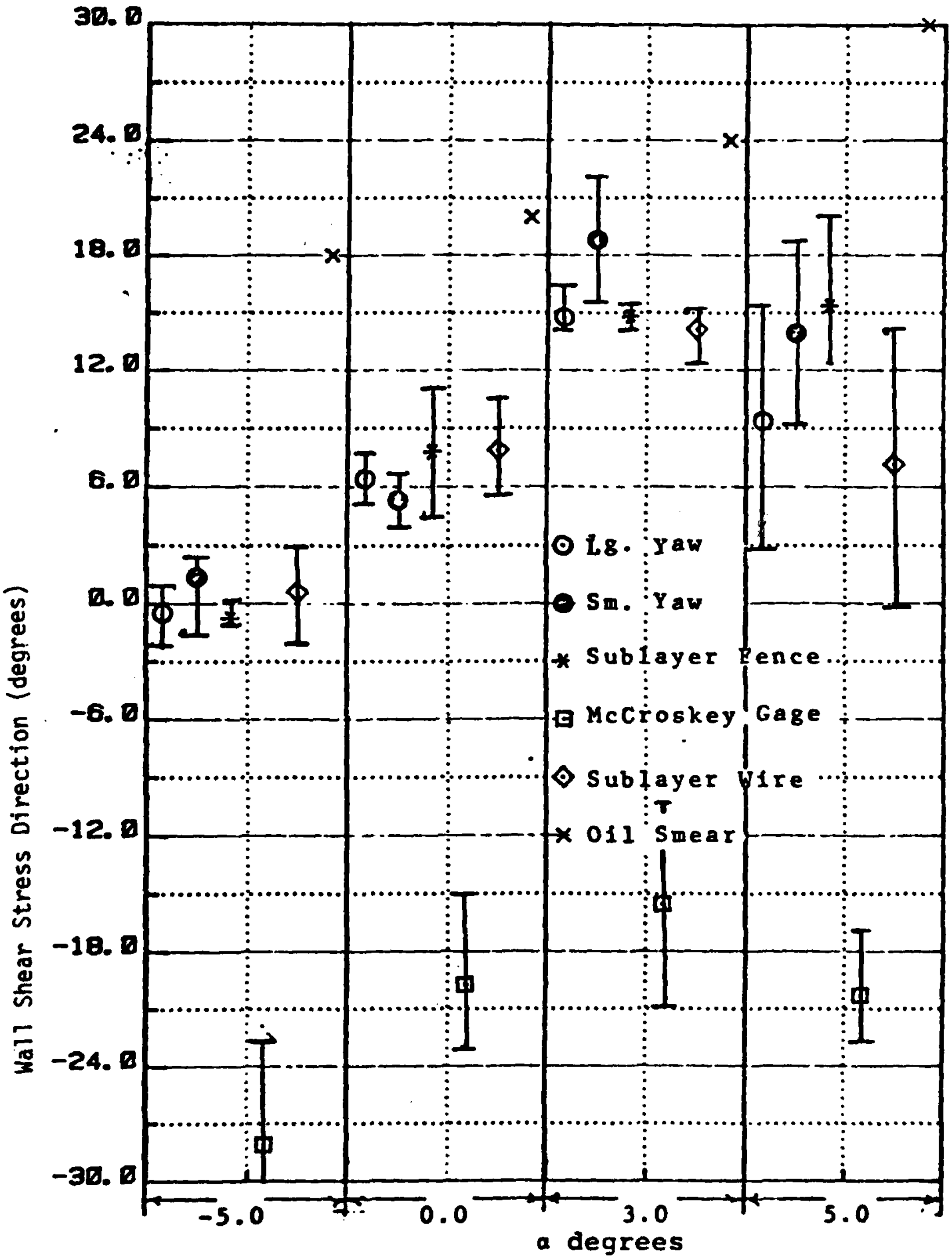

Figure 1. Comparison of the different techniques of wall shear stress measurement - direction of shear stress. (Data on swept airfoil NACA0012, from Craig [2]).

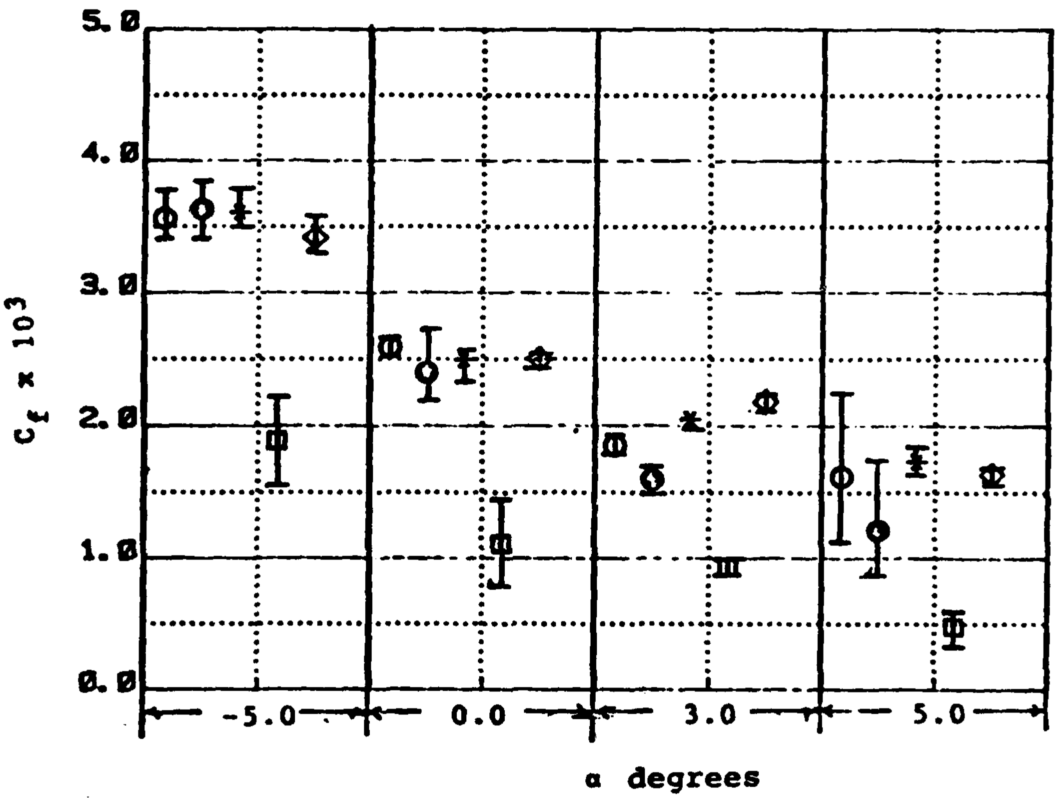

Figure 2. Comparison of the different techniques of wall shear stress measurement - magnitude of wall shear stress. (Data on swept airfoil NACA0012, from Craig [2]).

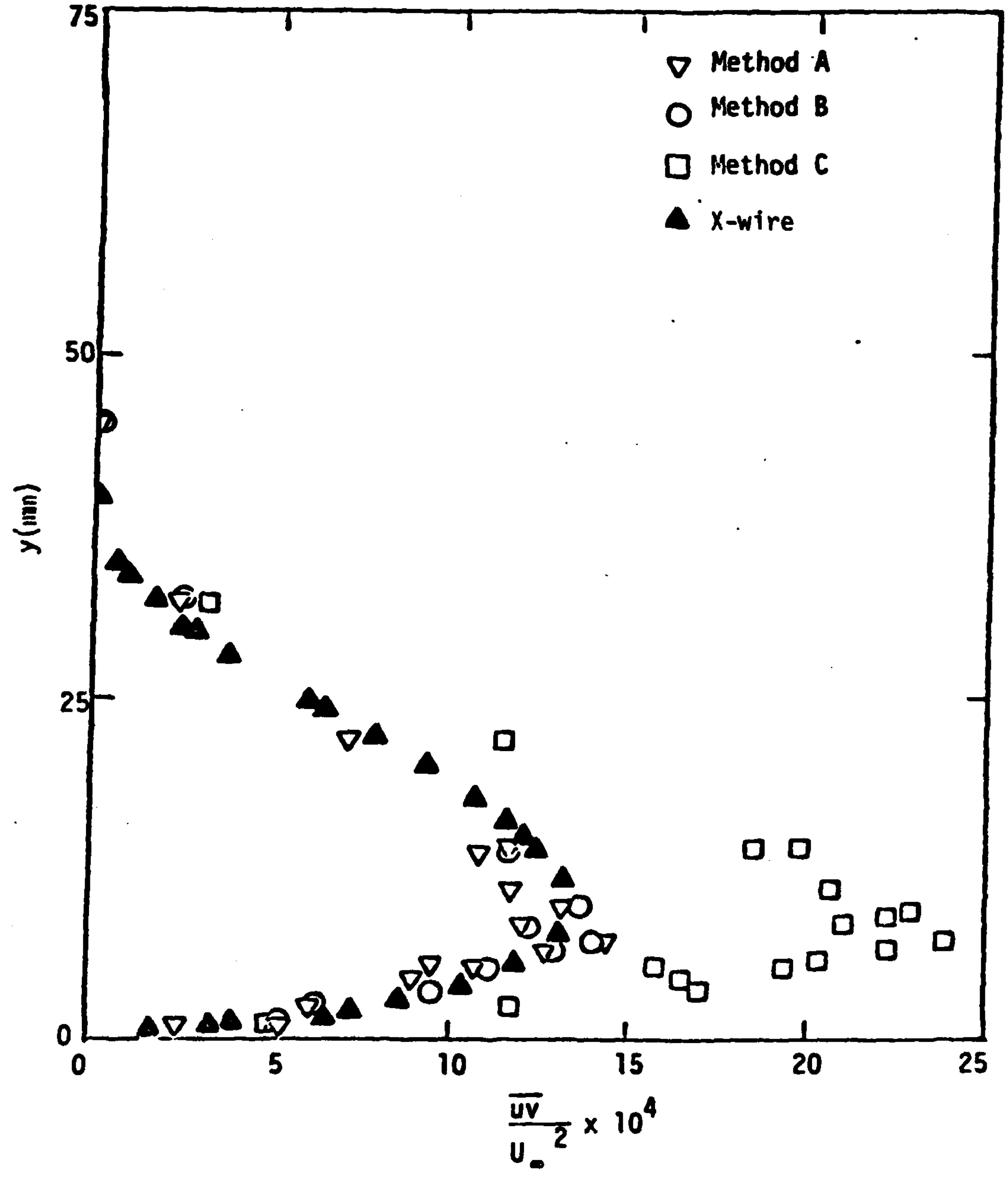

Figure 3. Comparison of three-wire probe measurements in the wake of a flat plate.

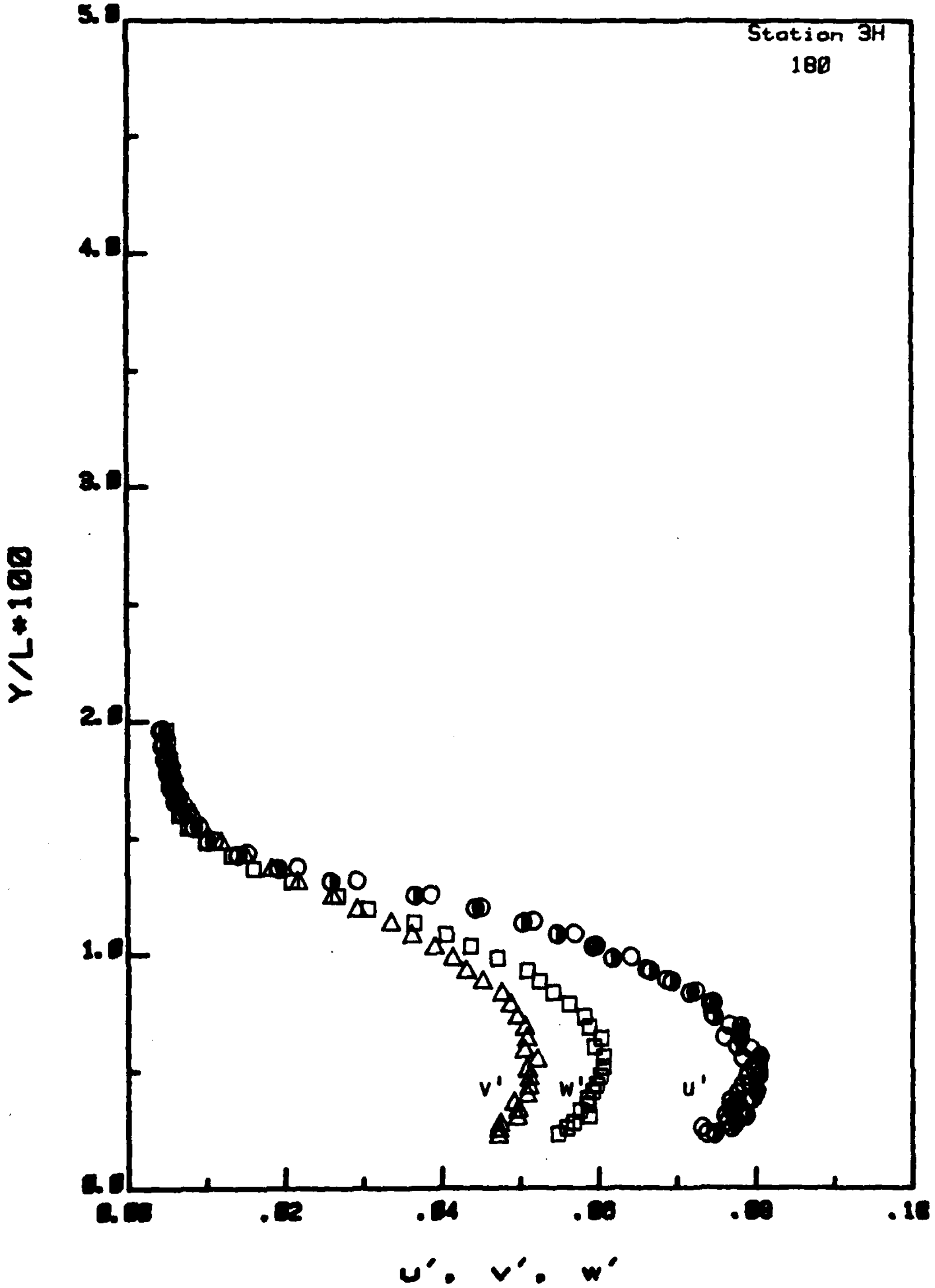

Figure 4. Turbulent Measurements on Leeward Plane of Symmetry at Station 3.

(a) Turbulence Intensities

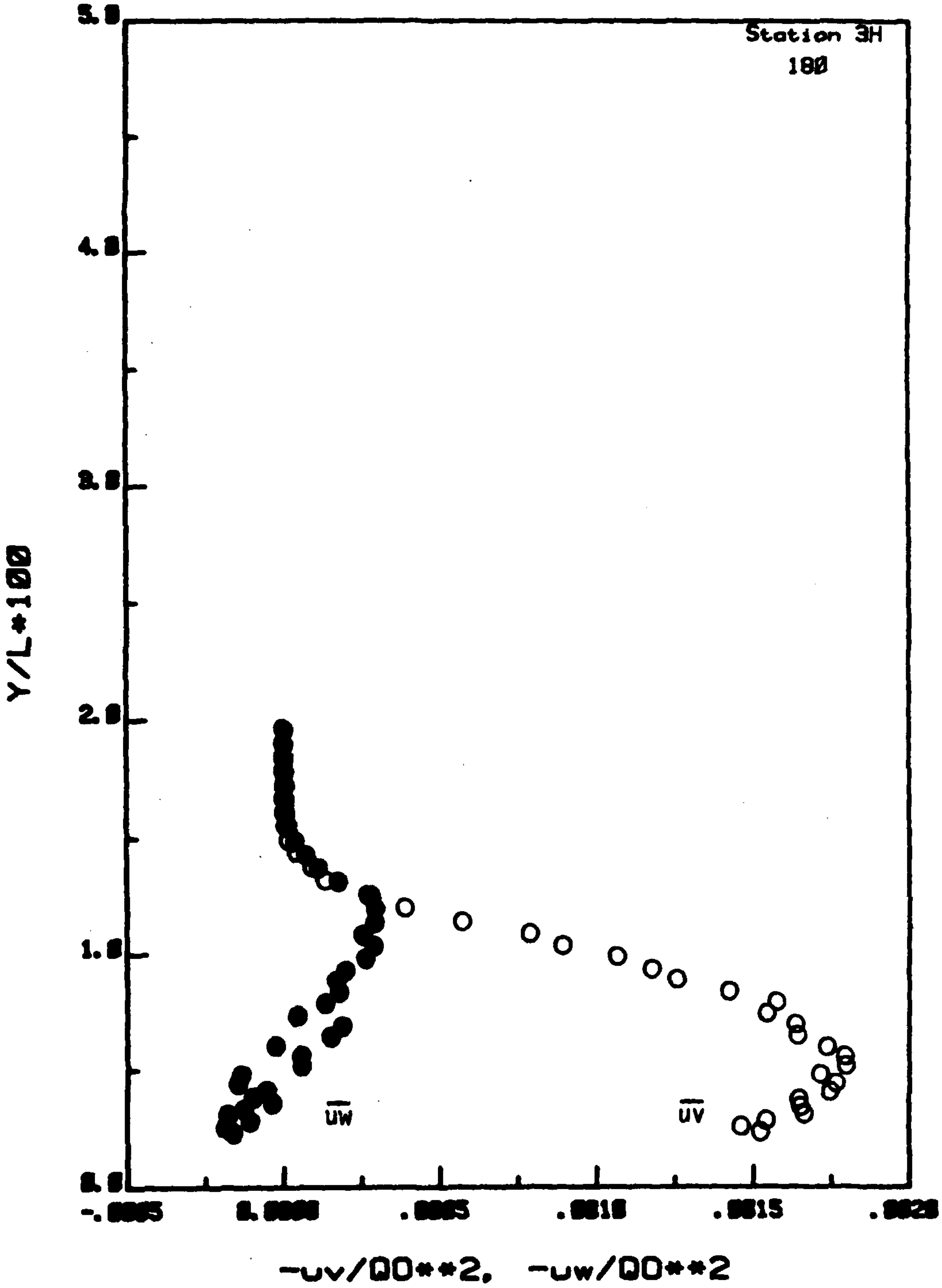

Figure 4. (b) Shear stresses

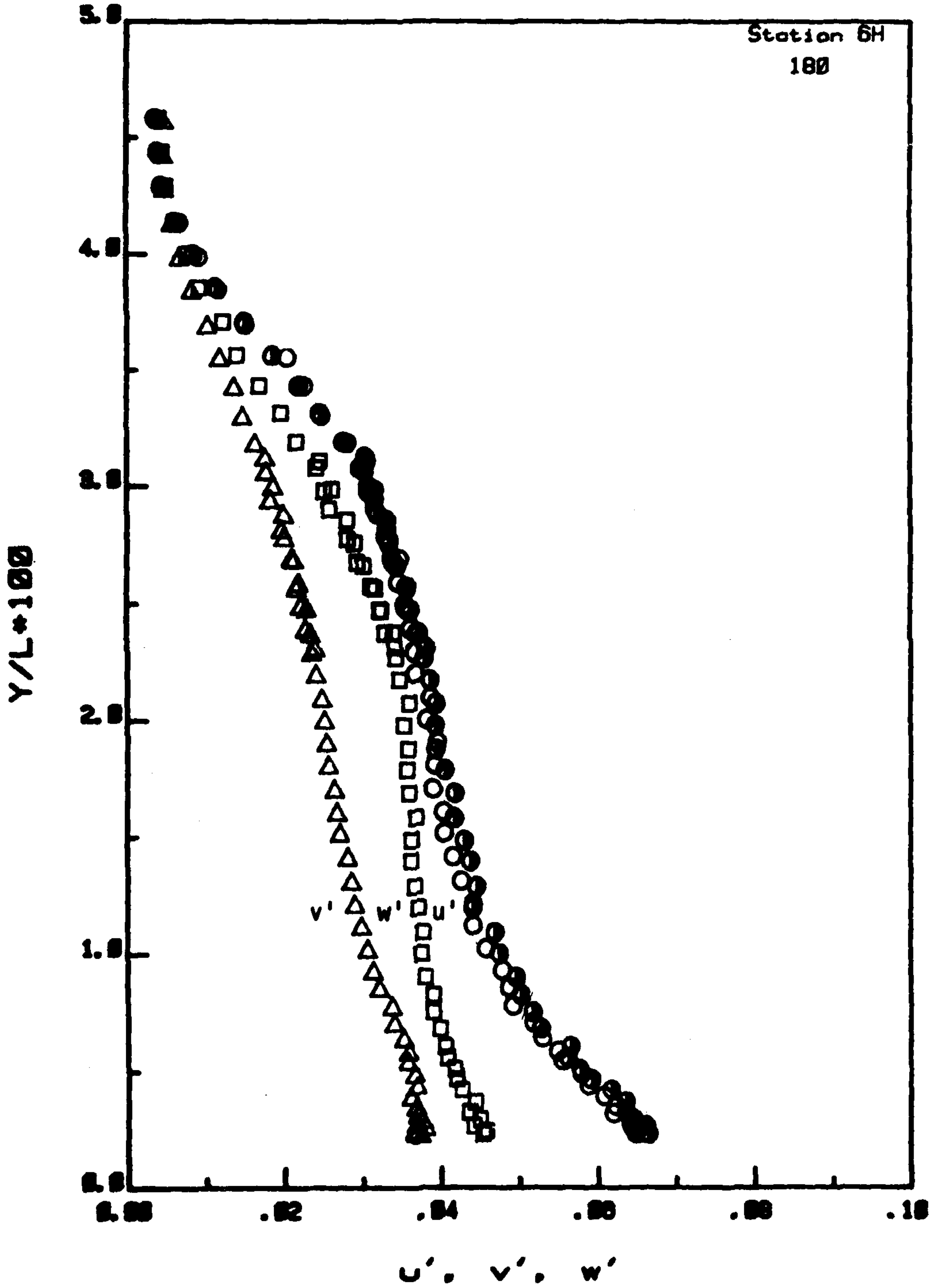

Figure 5. Turbulence Measurements on Leeward Plane of Symmetry at Station 6.
(a) Turbulence Intensities

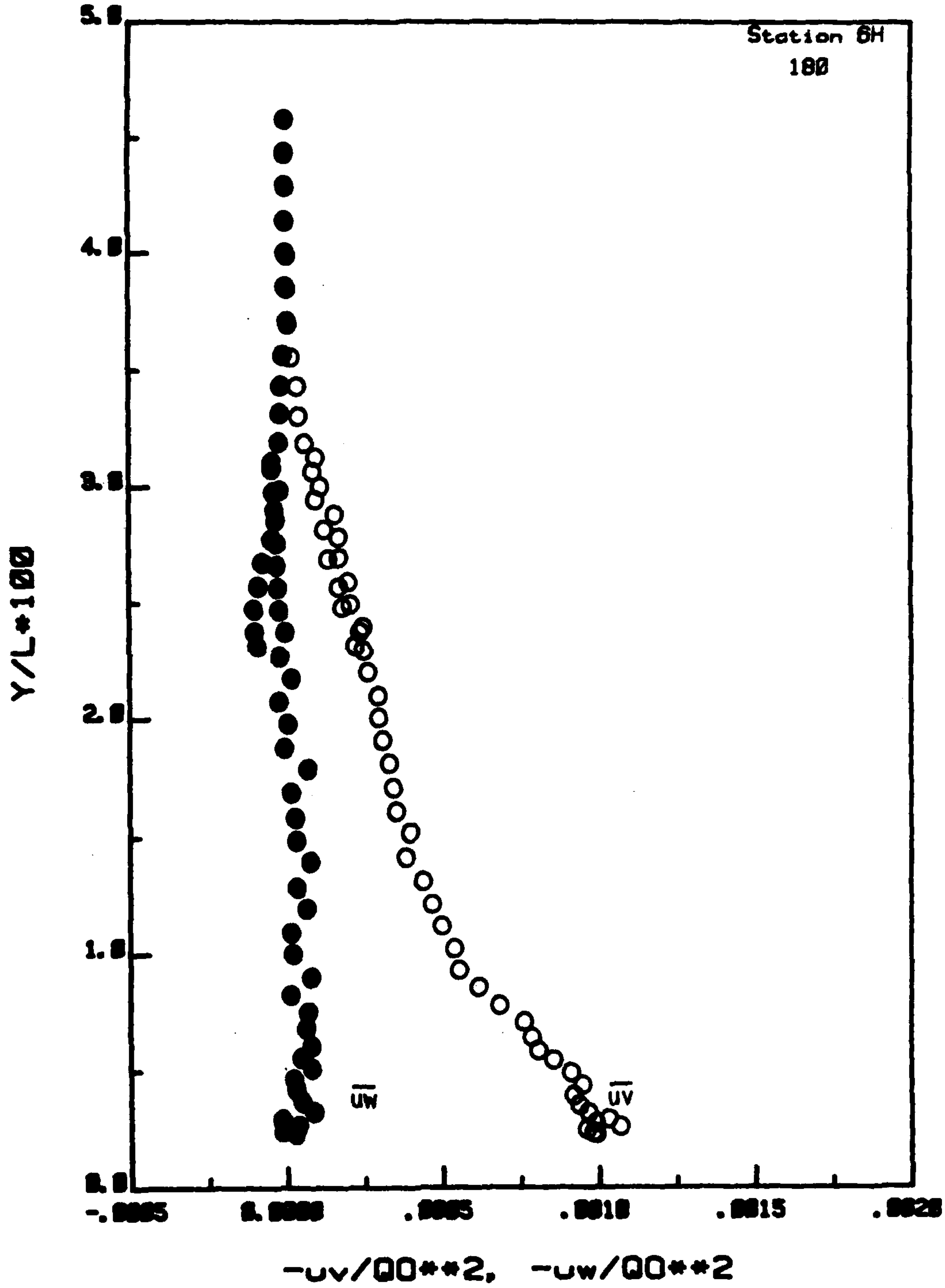

Figure 5(b). Shear Stresses.

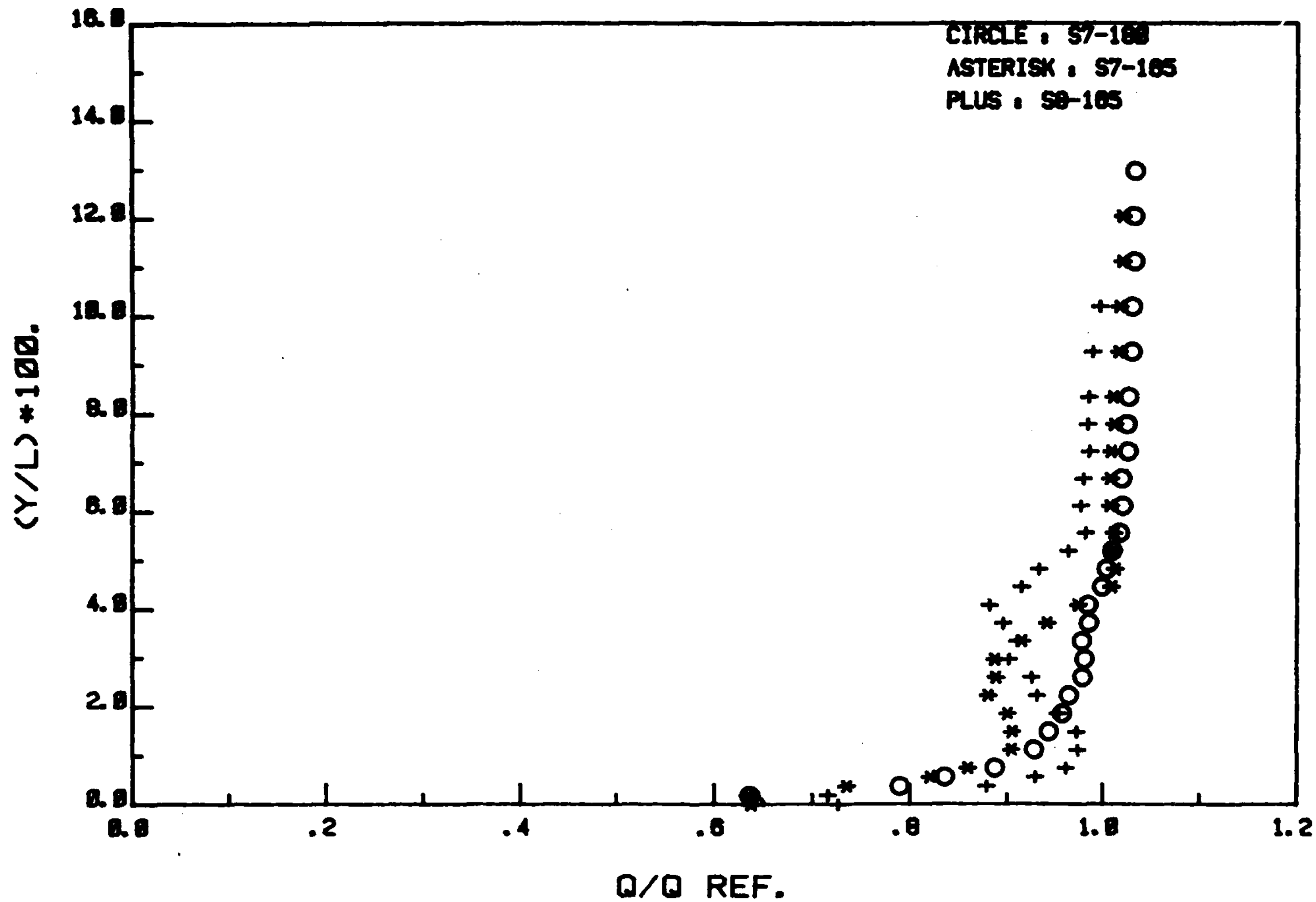

Figure 6. Resultant velocity at Stations 7 and 8. (Five-Hole Probe)
o Station 7 $\theta = 180^0$; * Station 7 $= 165^0$; + Station 8, $\theta = 165^0$

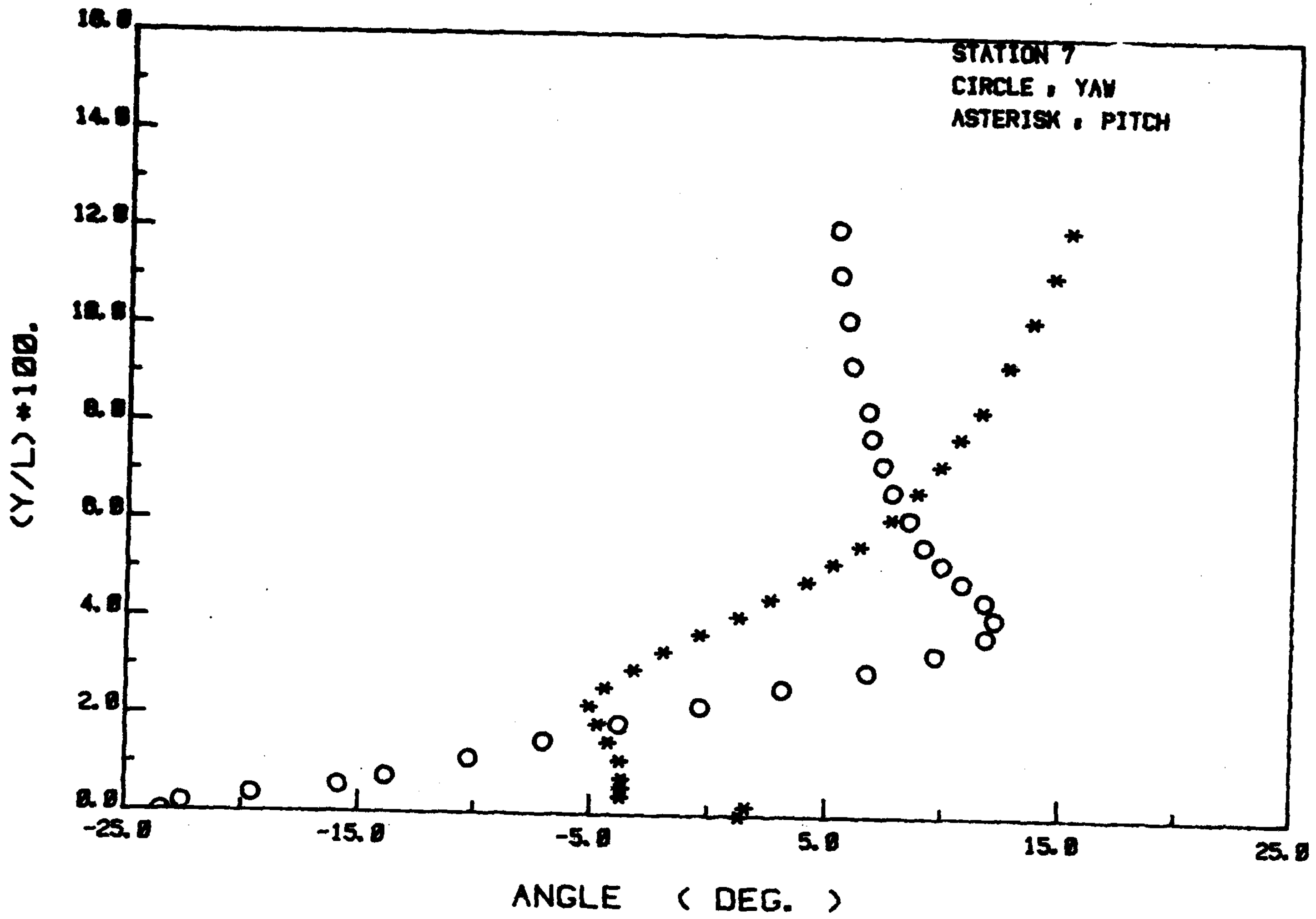

Figure 7(a) Yaw and Pitch Angles at Station 7, $\theta = 165^{0}$.

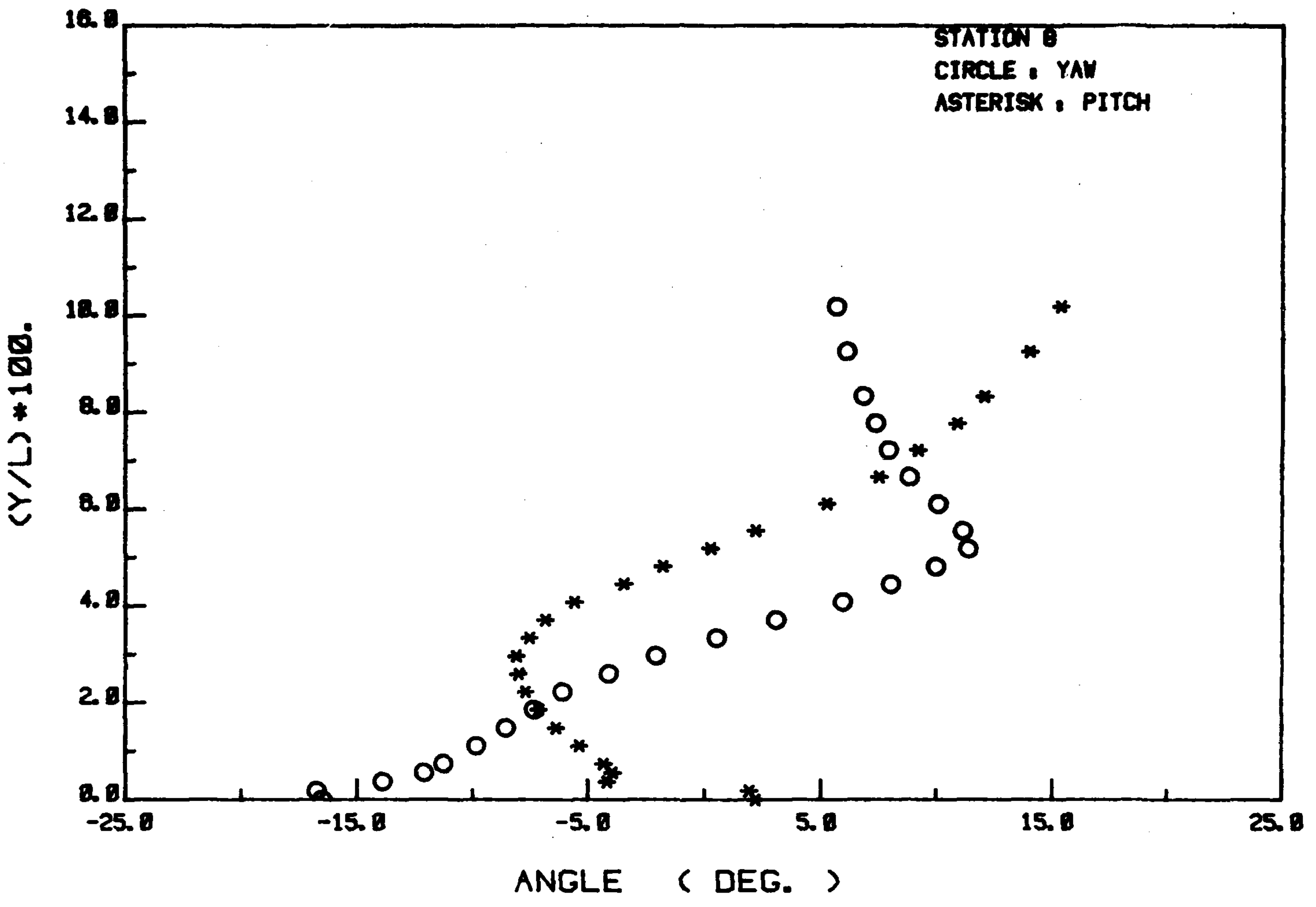

Figure 7(b). Yaw and Pitch Angles at Station 8, $\theta = 165^0$.

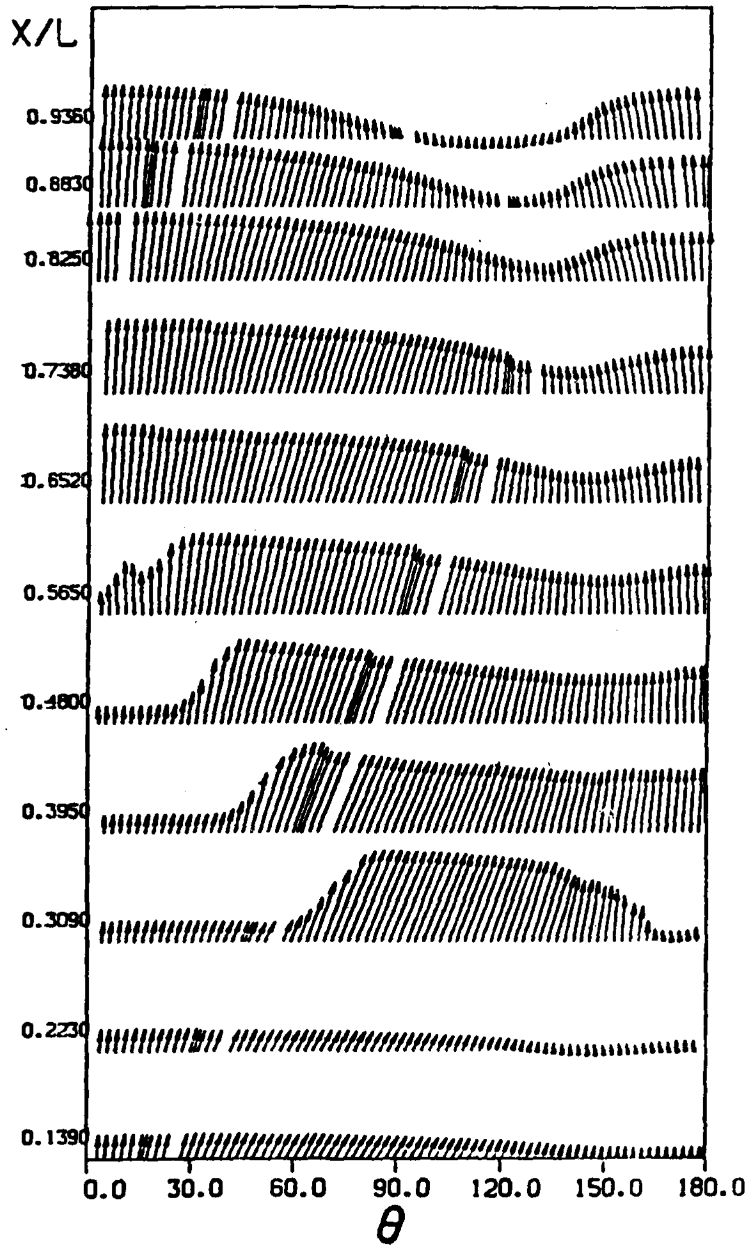

Figure 8(a) Measured Wall Shear Stress, $Re = 7.2 \times 10^6$

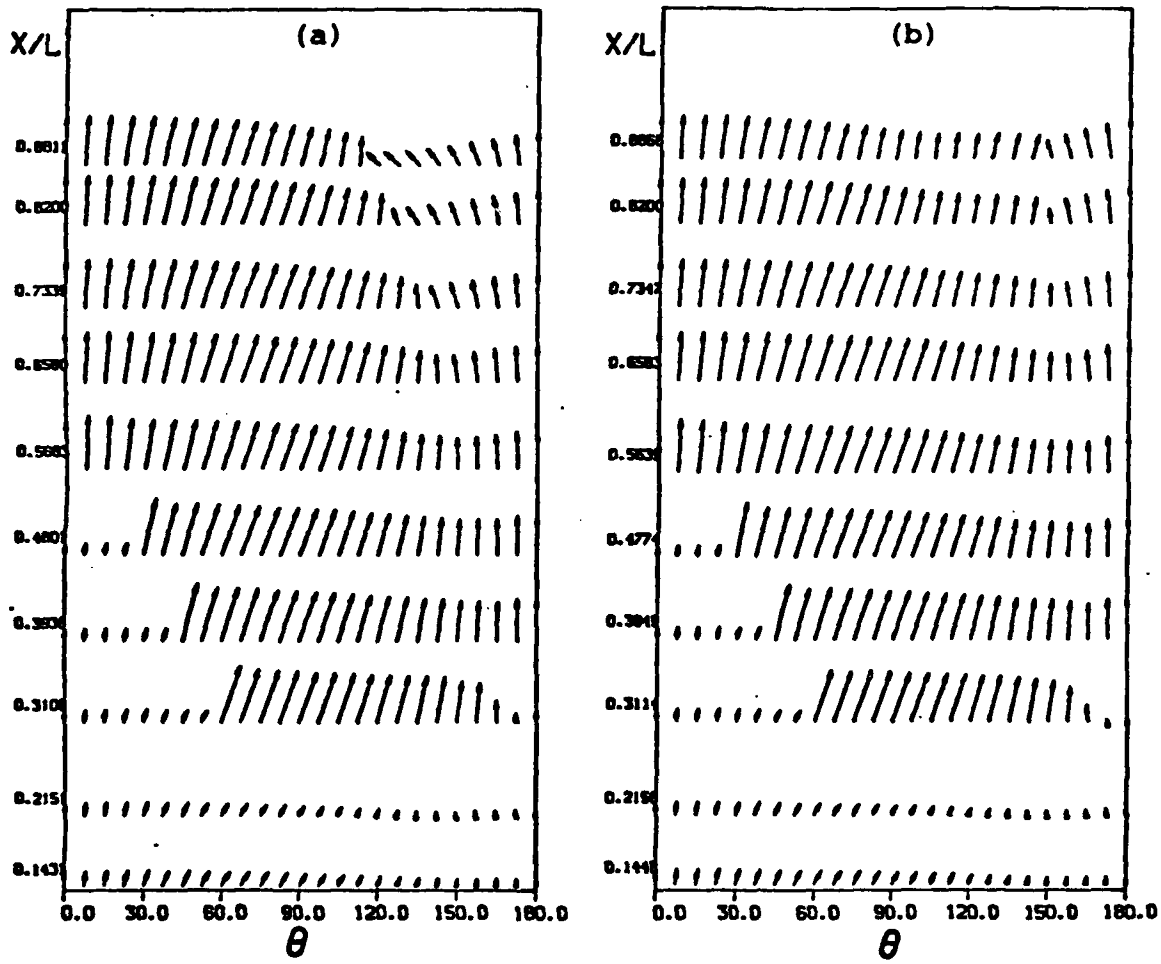

Figure 8(b) Calculated Wall Shear Stress, Re = 7.2×10^6

(a) Potential–Flow Pressure Distribution

(b) Experimental Pressure Distribution

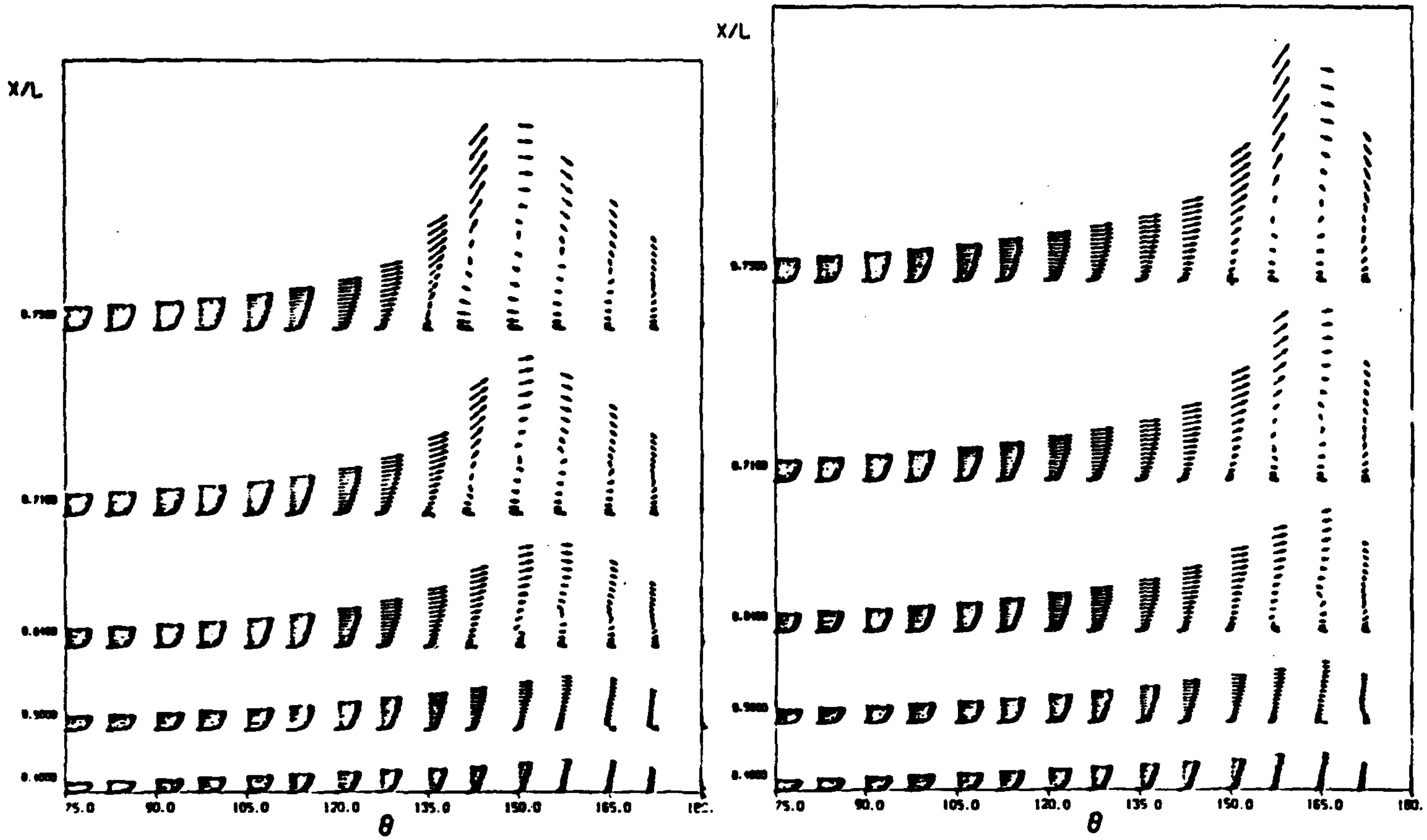

Figure 9 Velocity Vectors in the y–θ Plane, Re = 7.2×10^6

(a) Potential–Flow Pressure Distribution

(b) Experimental Pressure Distribution

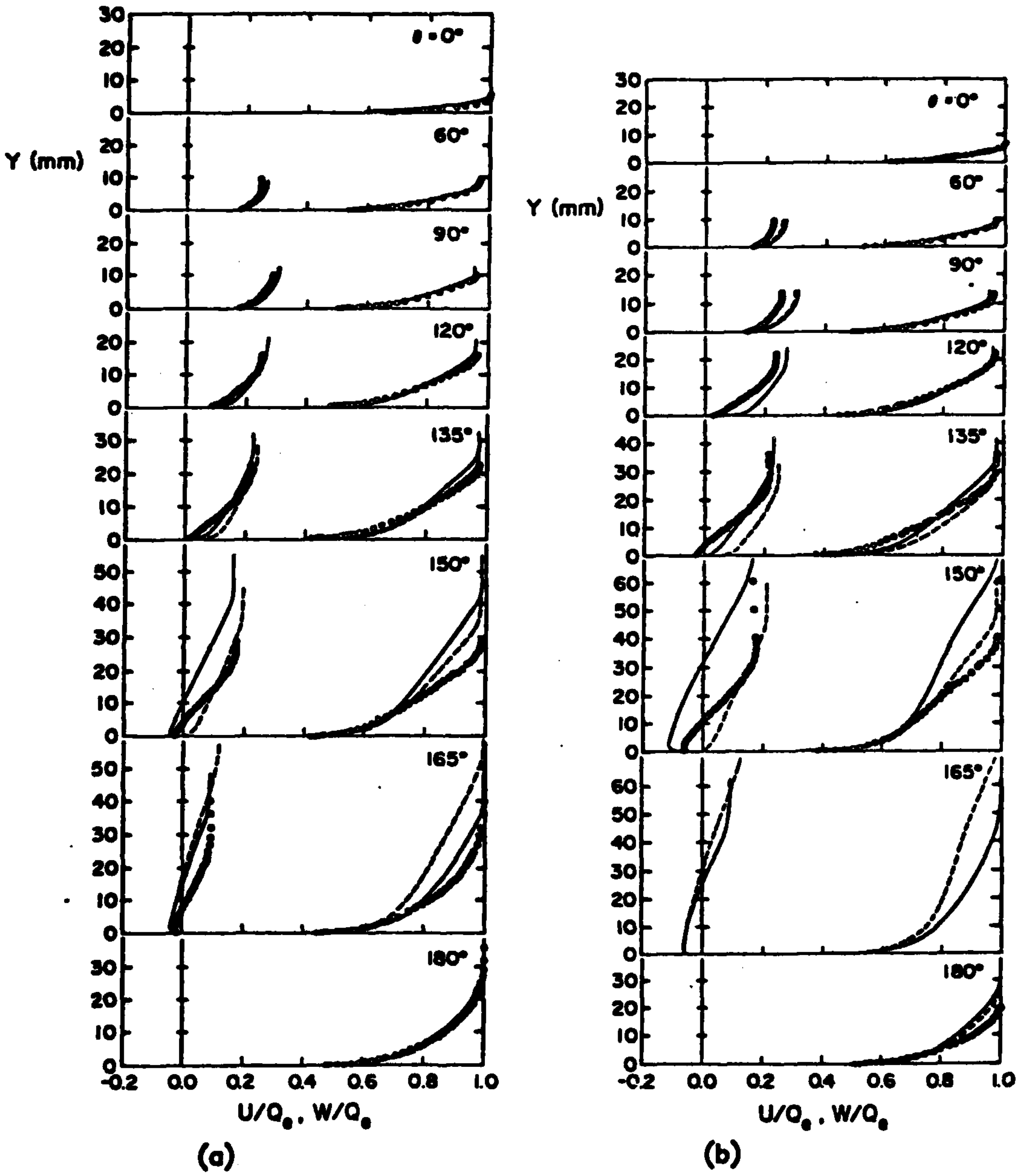

Figure 10. Axial and Circumferential Velocity Profies, Re = 7.2 x 10^6
(a) X/L = 0.64, (b) X/L = 0.71
---- Potential Flow Pressure, —— Measured Pressure,
o Experiment

END

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